

# Observation of VHE gamma-ray emission from the Active Galactic Nucleus 1ES1959+650 using the MAGIC telescope

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## ABSTRACT

The MAGIC Cherenkov telescope has observed very high energy (VHE) gamma-ray emission from the Active Galactic Nucleus 1ES1959+650 during six hours in September and October 2004. The observations were carried out alternated with the Crab Nebula, whose data were used as reference source for optimizing gamma/hadron separation and for flux comparison. The data analysis shows VHE gamma-ray emission of 1ES1959+650 with  $\sim 8\sigma$  significance, at a time of low activity in both optical and X-ray wavelengths. An integral flux above  $\sim 180$  GeV of about 20% of the Crab was obtained. The light curve, sampled over 7 days, shows no significant variations. The differential energy spectrum between 180 GeV and 2 TeV can be fitted with a power law of index  $-2.72 \pm 0.14$ . The spectrum is consistent with the slightly steeper spectrum seen by HEGRA at higher energies, also during periods of low X-ray activity.

*Subject headings:* 1ES1959+650, AGN, HBL, VHE gamma-ray, Cherenkov telescope

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## 1. Introduction

### 1.1. The VHE gamma-ray source 1ES1959+650

The Active Galactic Nucleus (AGN) 1ES1959+650 is an X-ray peaking BL Lacertae object selected from the Einstein Medium Sensitivity Survey (Elvis 1992). It is hosted by an elliptical galaxy at a redshift of  $z = 0.047$ . According to the unified model of AGNs, BL Lacertae objects have relativistic jets emerging from supermassive black holes accreting at a sub-Eddington rate, viewed under a small angle of sight (Padovani & Urry 1992). With decreasing luminosity, the peak frequency of the synchrotron emission from the relativistic jets seems to move to higher frequencies. The class of BL Lacs in which the synchrotron peak lies in the X-ray regime, are thus called HBLs (high frequency peaked BL Lacs). The mass of the central black hole (BH) in 1ES1959+650 has been estimated to be  $\sim 1.5 \cdot 10^8 M_\odot$  (Falomo et al. 2002), i.e. close to the BH mass of the HBL Mkn 421, the archetype of an extragalactic very high energy gamma-ray ( $\gamma$ ) source (Punch et al. 1992).

The first VHE  $\gamma$  signal from 1ES1959+650 was reported in 1998 by the Seven Telescope Array in Utah, with a  $3.9 \sigma$  significance (Nishiyama et al. 2002). Observing the source in 2000, 2001, and early 2002, the HEGRA collaboration reported only a marginal signal (Horns et al. 2002). In May 2002, the X-ray flux of the source had significantly increased. Both the Whipple (Holder et al. 2003) and HEGRA (Aharonian et al. 2003) collaborations subsequently confirmed also a higher VHE  $\gamma$  flux. Further high  $\gamma$  activity periods were detected in the same year, with some flares exceeding the Crab flux by a factor 2-3. An interesting aspect of the source activity in 2002 was the observation of a so-called *orphan flare* (viz. a flare of VHE  $\gamma$ s not accompanied by correlated increased activity at other wavelengths), recorded on 4 June by the Whipple collaboration (Krawczynski et al. 2004; Daniel et al. 2005). The HEGRA collaboration had observed another, less significant, orphan VHE signal during moonlight two days earlier (Tonello & Kranich 2003; Tonello 2005). Both flares in VHE  $\gamma$ s, observed in the absence of high activity in X-rays, are not expected from the synchrotron self-Compton (SSC) mechanism in relativistic jets (Kellermann & Pauliny-Toth 1969). For other HBLs, models based on the SSC mechanism (Ghisellini et al. 1998) can successfully explain most of the VHE  $\gamma$  production. Future observations of 1ES1959+650, therefore, are of special importance.

This paper is structured as follows: after a brief description of the MAGIC telescope, we present in Sect. 2 the data analysis using image parameters for gamma-hadron separation, and the reconstruction of the direction and energy of the measured photons. Results are shown in Sect. 3 comparing with data from the Crab Nebula taken around the same time and under similar zenith angles. Finally, we discuss in Sect. 4 some implications of our findings

for VHE emission models and the extragalactic background light.

## 1.2. The MAGIC Cherenkov telescope

The MAGIC telescope represents a new generation of Imaging Air Cherenkov Telescopes (IACTs) for  $\gamma$  astronomy. Its design has been optimized to achieve a trigger threshold lower than was possible with previous IACTs (MAGIC eventually is to reach a trigger threshold of 30 GeV at zenith). The low threshold will make it an ideal instrument for the study of VHE  $\gamma$  sources that have spectral cut-offs below 100-200 GeV, such as pulsars, medium redshift AGNs, etc.

The MAGIC parameters and performance have been described elsewhere (Cortina et al. 2005; Baixeras et al. 2004). The MAGIC mirror has a diameter and focal length both of 17m; its camera comprises 576 hemispherical photo-multiplier tubes with diffuse lacquer coating (Paneque et al. 2004) and specially shaped light collectors, both enhancing quantum efficiency. The camera has a field of view (FOV) of  $3.5^\circ$ .

The MAGIC telescope is located on the Canary Island of La Palma ( $28.2^\circ\text{N}$ ,  $17.8^\circ\text{W}$ , at 2225 m asl). From this location, 1ES1959+650 is visible from May to October under a zenith angle of  $36^\circ$  at culmination. At a mean observation angle of  $40^\circ$ , the threshold for the physics analysis is about twice that at zenith. We present here an analysis down to 180 GeV. Past Whipple and HEGRA observations were carried out above 700 GeV and above 1 TeV, respectively.

## 2. Data Analysis

The analysis presented here is restricted to  $\gamma$ s with an energy above 180 GeV. At such energies, we can discriminate hadronic and electromagnetic showers using the classical techniques pioneered by the Whipple collaboration, described in (Fegan 1997). The shower image in the camera is parameterized to obtain several test statistics (Hillas 1985) describing the image shape and orientation (also called image parameters or discriminant quantities). The parameters are used to reject hadronic background events by defining, in the space of these parameters, limiting values, *cuts*, that discriminate between  $\gamma$ - and hadron-induced images. The parameters also permit reconstructing the arrival direction and the energy of the original  $\gamma$ .

Table 1 shows the summary of the data collected from 1ES1959+650, Crab Nebula, and OFF-source. This period in fall 2004 corresponds to the end of the MAGIC commissioning

phase. The zenith angles for these observations are all in the range 36 - 46°.

Table 1: *Statistics of the raw data analyzed.*

Source	Date in 2004	Total time	N. events
1ES1959+650	Sept. 6-7, Oct. 7, 10, 14-17	6 h 31 min	4.4 M
Crab	Sept. 13-16, 21-23	2 h 17 min	1.7 M
OFF-source	Sept. 8, 10-13, 17	2 h 49 min	2.3 M

Generally, the Crab Nebula with its very stable flux is considered a reference source, viz. a standard candle, for VHE  $\gamma$  astronomy. For that reason, Crab data observed with MAGIC were selected such as to match telescope operation conditions, in time and zenith angle, to those during the observation of 1ES1959+650. So-called OFF-source data are collected by pointing the telescope to a sky section near the source, where no  $\gamma$  signal is expected in the field of view. These data are used as crosscheck of the recorded cosmic ray background.

After quality cuts (rejection of accidental triggers due to noise etc.), and correcting for the dead-time of the data acquisition system, the effective observation time for 1ES1959+650 amounts to  $\sim 6$  hours. The optimal cut values of image parameters for the  $\gamma$ -hadron separation was obtained using Monte Carlo data<sup>1</sup>, the parameter cut values being 'trained' to obtain a signal with the maximum significance from the  $\sim 2$  hours of Crab Nebula data observed at the same zenith angle. These cuts were then applied to the 1ES1959+650 data sample, without further optimization. In our analysis, we used eight image parameters<sup>2</sup>; the optimization procedure used the *Random Forest* method, which optimizes the transformation of the parameter space into a single variable, called *hadronness* (Breiman 2001; Bock et al. 2004). More details on the analysis can be found in Tonello (2005).

Two of the image parameters are of particular importance: the variable SIZE, expressed in number of photo-electrons in the camera, is, for an impact parameter between  $\sim 50$ m and  $\sim 150$ m (equivalent to the image parameter DIST between  $0.3^\circ$  and  $1^\circ$ ), to first order proportional to the energy of the incoming  $\gamma$ ; the variable ALPHA, the angle in the image between the major axis and the direction of the source, shows most clearly the existence of a signal. ALPHA is not included in the optimization process; instead, after optimizing cuts in the other parameters, we derive from the ALPHA distribution (Fig.1) the significance of

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<sup>1</sup>The MAGIC Monte Carlo programs are based on Corsika 6.019, see Heck & Knapp (2002).

<sup>2</sup>The parameters are ALPHA, SIZE, DIST, transformed WIDTH and LENGTH, two different concentration parameters, and an asymmetry parameter.

the signal (using (Li & Ma 1983), formula 17). Finally, the data are required to satisfy low ALPHA values, thus selecting only showers that point to the source position.

### 3. Results

#### 3.1. Alpha plot and comparison with Crab

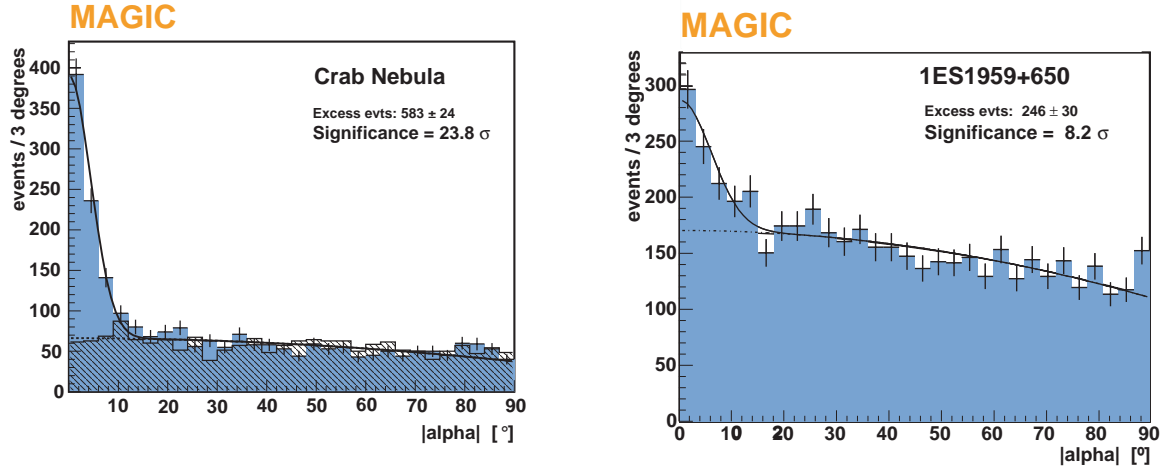


Fig. 1.— *ALPHA* plots of Crab (left) and 1ES1959+650 (right), after cuts on image parameters. Both diagrams show the second-order curve used for estimating the background at low *ALPHA* (up to  $9^\circ$ ). In the left diagram (Crab), we also have added the (normalized) OFF-source data.

In Fig.1 (left) we show the distribution of the image parameter *ALPHA* for the Crab Nebula, together with the OFF-source data normalized to the ON-source data between  $20^\circ$  and  $90^\circ$ . Here we chose a selection of events in terms of SIZE, corresponding to a threshold  $>300$  GeV <sup>3</sup>. In Fig.1 (right), the *ALPHA* distribution of the 1ES1959+650 data sample is shown, after applying the parameter cuts optimized using the Crab sample. The background for the Crab data under the signal was estimated both from the OFF-source events and by extrapolating the *ALPHA* distribution from ON-source events between  $20^\circ$  and  $90^\circ$ , using a simple second-order formula ( $C_1 + C_2 \cdot \text{ALPHA}^2$ ). Both methods give the same result; we thus used the same formula of extrapolation from the ON-source events outside the excess peak, for both Crab and 1ES1959+650.

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<sup>3</sup>This data selection has been chosen such as to allow applying a constant *ALPHA* cut of  $9^\circ$  to the entire sample. Including lower energy events adds more background and reduces significance. The optimization of the full sample, including events of smaller SIZE, has been done separately.

The significance of the 1ES1959+650 detection is  $8.2\sigma$ , with  $246 \pm 30$  excess events (after all cuts) in  $\sim 6.0$  hours, the signal from Crab Nebula corresponds to  $\sim 23.8$  sigma and  $583 \pm 24$  excess events in  $\sim 2.1$  hours.

We obtain a integral VHE  $\gamma$  flux from 1ES1959+650 above 180 GeV of  $(3.73 \pm 0.41 \pm 0.35) \cdot 10^{-11}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  (the errors given are statistical and an estimate for systematics, respectively)<sup>4</sup>. For the flux above 300 GeV, the result is  $(1.57 \pm 0.17 \pm 0.30) \cdot 10^{-11}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . These flux values correspond to 0.20 and 0.17 Crab units, respectively, when comparing to the Crab flux measured by MAGIC.

We also analyzed the data set using a completely independent analysis chain<sup>5</sup>, and obtained, within statistical limits, the same significance and flux.

### 3.2. The light curve

Most blazars known to emit VHE  $\gamma$ s were detected at times of strong VHE  $\gamma$  flaring, and correlated with strong X-ray variability during the same period. For our 6 hours observation time of the 1ES1959+650, only modest tests of the flux variation are possible. We show in Fig.2 and in table 2 a flux analysis for each night, indicating that the source was basically in the same (low) state during the time covered by our observation; corrections for small differences in the zenith angle came out to be negligible.

### 3.3. Comparison with simultaneous observations at other wavelengths

Strong VHE  $\gamma$  emission from an AGN leads to the question whether the source was active also at other wavelengths. If the  $\gamma$  emission is due to the inverse-Compton scattering of accelerated electrons, their corresponding synchrotron emission must show up at lower energies. Most observations of other sources are indeed in line with the correlated X-ray variability expected from synchrotron-self-Compton models, e.g (Krawczynski 2003; Inoue & Takahara 1996). Figures 3 and 4 show the light curves of 1ES1959+650 in the X-ray and optical domains. The X-ray data are based on published RXTE-ASM X-ray flux data (ASM 2005), the optical light curve is provided by the Tuorla Observatory Blazar Moni-

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<sup>4</sup>For this estimate of the flux, the small correction for the 'dead time' of the electronics readout was not considered.

<sup>5</sup>using dynamical supercuts as described in Kranich (1997)

Table 2: *Analysis of 1ES1959+650 data divided into single nights of observation.*

Date MJD	Excess evts/min	Sign. $\sigma$	Flux ( $> 300$ GeV) $10^{-11}$ ph.el. $\text{cm}^{-2} \text{s}^{-1}$
53254.0	$0.82 \pm 0.22$	3.7	$1.83 \pm 0.47$
53254.9	$0.54 \pm 0.24$	2.2	$0.74 \pm 0.48$
53285.0	$0.95 \pm 0.28$	3.4	$1.76 \pm 0.67$
53287.9	$0.95 \pm 0.30$	3.2	$1.34 \pm 0.68$
53292.9	$0.53 \pm 0.31$	1.7	$1.38 \pm 0.75$
53293.9	$1.26 \pm 0.27$	4.7	$2.69 \pm 0.67$
53294.9	$0.69 \pm 0.18$	3.9	$1.23 \pm 0.40$

toring Program (Tuorla 2005). No strong activity in X-rays or in the optical was observed during the period of the VHE  $\gamma$  studies reported here. This fact and the absence of significant time variability lead to the tentative conclusion that the reported VHE  $\gamma$  emission of 1ES1959+650 does not follow the pattern observed in other AGNs during flaring periods. Future observations over longer periods will shed more light on the nature of the quiescent VHE emission of 1ES1959+650 (see Sect. 4 below).

### 3.4. The VHE $\gamma$ spectrum and a comparison with the Crab spectrum

The spectra for Crab and 1ES1959+650 measured in fall 2004 are shown in Fig.5. Both spectra are consistent with a simple power law, albeit with a spectral index smaller than reported at higher energies. The lines show fits to the spectra between 180 GeV and 2 TeV corrected for spill-over factors, using as ansatz an unbroken power law; the fits give slopes of  $-2.72 \pm 0.14$  for 1ES1959+650 and  $-2.41 \pm 0.05$  for the Crab, respectively. There is strong evidence of the spectrum of the 1ES1959+650 being steeper than that of the Crab over this energy range.

In Fig.6 we show a comparison with spectral data taken by HEGRA in 2002 at higher energies (Aharonian et al. 2003), with a slope of  $-3.18 \pm 0.17$ . The energy overlap of past and current data is small, demonstrating the progress in accessing lower energies with the MAGIC telescope. Past spectral descriptions required a cut-off parameter of about 3 TeV, in order to take into account possible absorption due to the cosmic infrared background. Our data are in an energy range where the effects of such an absorption process are weak, thus a simple power law should be sufficient to describe the data.



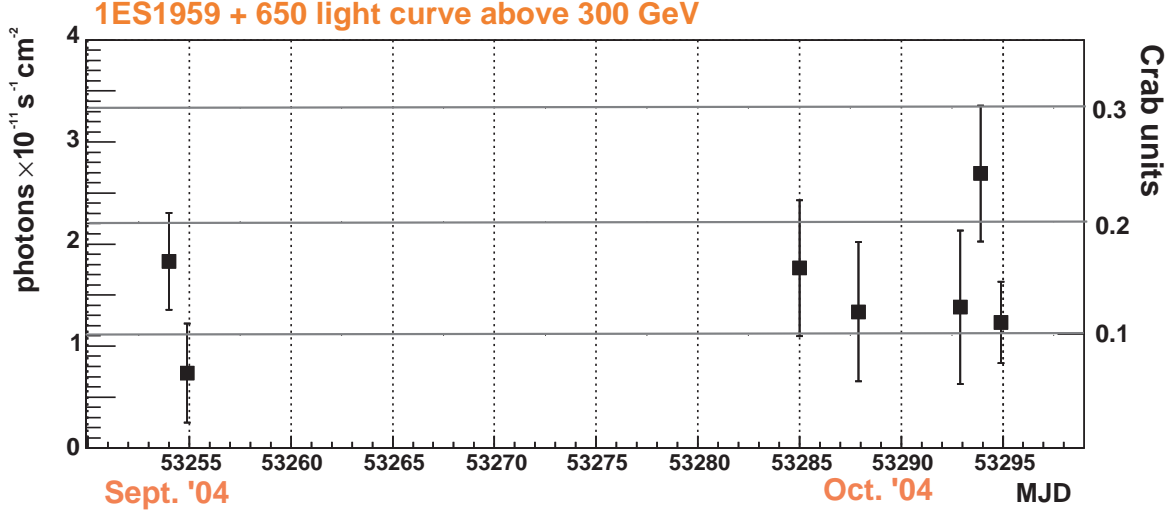


Fig. 2.— *Light curve for 1ES1959+650 as observed by MAGIC during seven nights*

#### 4. Discussion and Conclusions

The HBL 1ES1959+650 has been clearly detected with the MAGIC telescope, in a few hours observation time during September and October 2004, at a mean zenith angle of  $40^\circ$ . During that period, the source was in a quiescent state both in X-rays and at optical wavelengths. In the same period, Crab Nebula and OFF-source data were recorded under comparable observational conditions.

For the first time, 1ES1959+650 has been observed down to 180 GeV, a limit much lower than achieved in previous experiments. The energy spectrum between 180 GeV and 2 TeV is compatible with a power law of slope  $-2.72 \pm 0.14$ . A crude variability analysis over the period of observation has shown no significant variation of the  $\gamma$  flux. The quiescent spectrum can be considered to match the spectrum measured by HEGRA at higher energy during past periods of equally low X-ray activity. We therefore tentatively conclude that a steady VHE emission component has been identified in the spectrum of 1ES1959+650.

EGRET has observed (Strong et al. 2004) a diffuse  $\gamma$  spectrum (a part of the extragalactic background light, or EBL) in the energy range 100 MeV - 100 GeV. The question arises if emission from multiple VHE  $\gamma$  sources of the 1ES1959 type in a low state of activity could produce such a spectrum, when extrapolated to higher energies. One can estimate that about 400 such sources would be needed. No complete HBL catalogue for the entire sky exists, but this number of HBLs at redshift  $z < 0.5$  can be expected from the EMSS (Elvis 1992) on a purely statistical basis. However, their mean X-ray flux is much lower than that of 1ES1959+650. Adopting the observed VHE/X-ray spectral index of  $\alpha_{X\gamma} \simeq 1$

for the quiescent spectrum, the cumulative VHE flux of HBLs would thus be insufficient to explain the observed diffuse  $\gamma$  spectrum. In agreement with this finding, the sky positions of high energy photons ( $> 10$  GeV) observed with EGRET do not generally coincide with the positions of HBLs (Thompson et al. 2005), indicating that other contributions to the EBL may also be important (Elsaesser & Mannheim 2005). In this context it should be noted that more measurements of other  $\gamma$ -emitting AGNs during periods of low X-ray activity would be important to shed light on these questions.

Explaining the observed quiescence spectrum by a one-zone SSC model is possible, but with some difficulty, since the implied relativistic electron pressure exceeds the magnetic pressure, leading to an unstable situation. SSC models, on the other hand, clearly fall short of explaining the orphan flares seen in previous observations of 1ES1959+650 (Krawczynski et al. 2004; Daniel et al. 2005; Tonello & Kranich 2003). The quiescence spectrum and the flares both seem to indicate the presence of an additional high energy electron population, possibly of hadronic origin (Boettcher 2005; Mannheim 1993; Massaro et al. 2004), or proton synchrotron radiation (Aharonian 2000). Short variability time scales might reflect dynamical effects in shock-in-jet models, or the short cooling times of protons at ultra-high (up to  $10^{19}$  eV) energies (Rachen & Meszaros 1998).

Multi-wavelength monitoring campaigns are required to further reveal the nature of the VHE emission component in 1ES1959+650. Such monitoring should also include future large neutrino observatories: the models based on the presence of a significant hadronic component of the 1ES1959+650 jet, e.g. (Boettcher 2005), predict in a natural way also detectable neutrino fluxes. The AMANDA collaboration, operating a neutrino telescope in the southern hemisphere, recently reported five recorded neutrino events from the direction of 1ES1959+650, over a total observation period of four years (Bernardini et al. 2005). Three events coincided with 1ES1959+650 flares; one is coincident with the orphan flare observed by the Whipple collaboration. While these observations are tantalizing, but not yet statistically compelling, they do demonstrate that neutrino astronomy has reached the stage at which fluxes at the level of the  $\gamma$  fluxes observed with IACTs can be probed. Even for neutrino-to- $\gamma$  ratios smaller than unity, ICECUBE should soon provide the necessary experimental sensitivity (Halzen & Hooper 2005).

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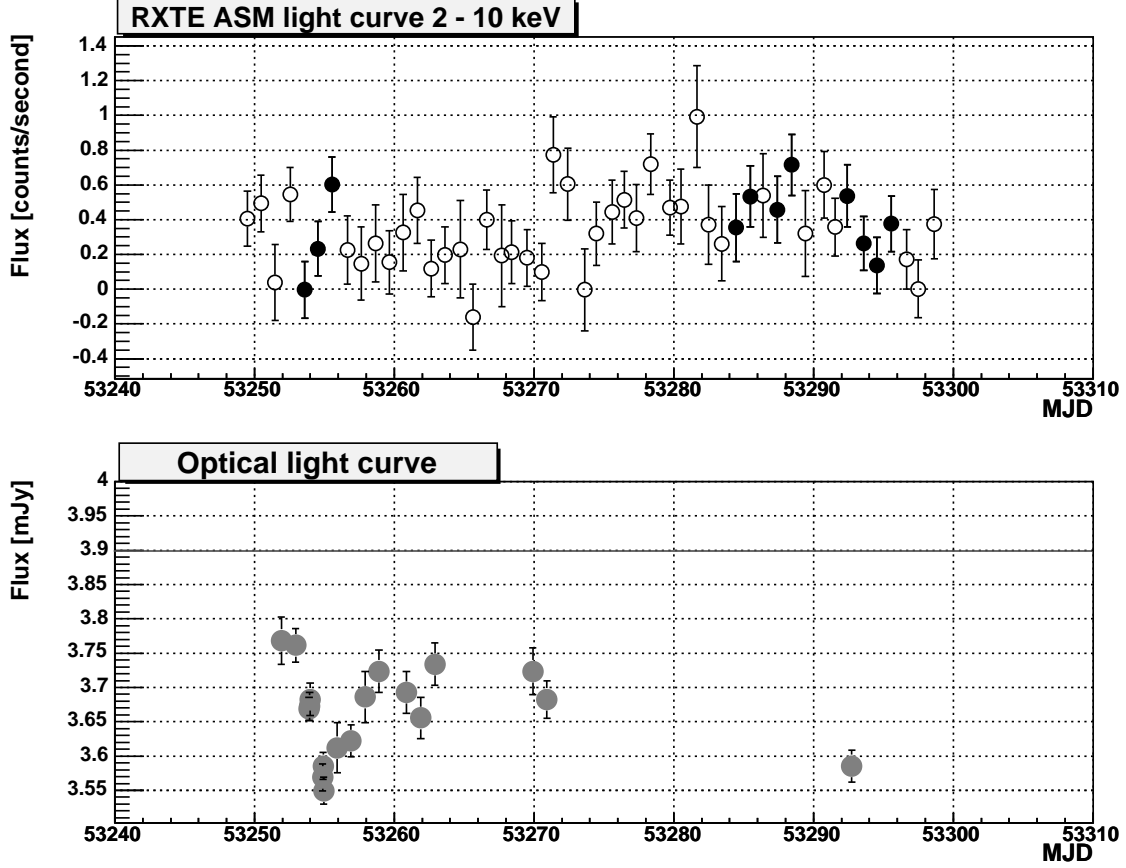


Fig. 3.— *Top: Light curve in X-rays for 1ES1959+650 during the months of September and October 2004 (from published RXTE-ASM data). The full circles indicate those recorded during the period of  $\gamma$  observations with MAGIC. Bottom: Optical light curve for the same period (from the Tuorla Blazar Monitoring Program). The line at 3.9 mJy gives the average flux over nearly two years (2002-09-10 to 2004-08-25) before the MAGIC observations: during our observations, the optical activity was particularly low.*

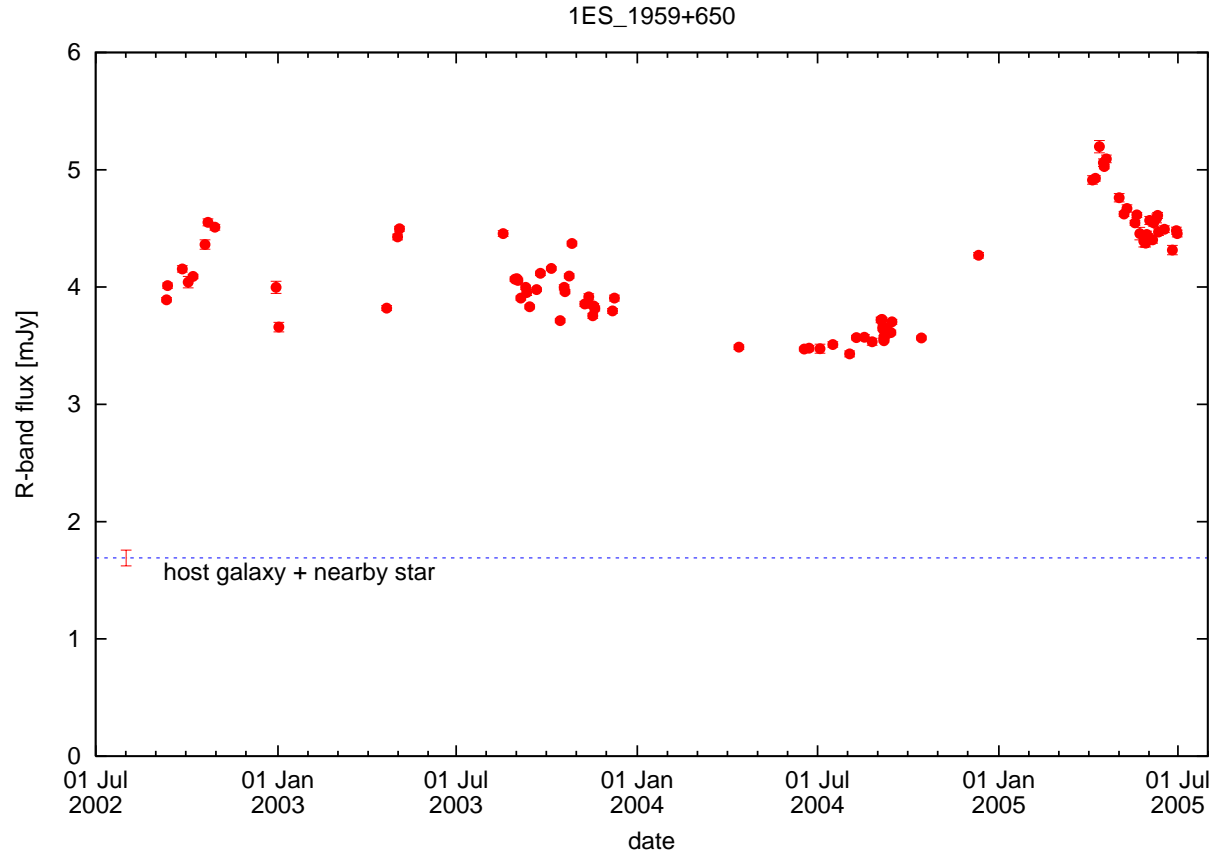


Fig. 4.— Full circles: light curve in optical for 1ES1959+650 from July 2002 to January 2005 (from the Tuorla Blazar Monitoring Program). The luminosity of the host galaxy is also reported.

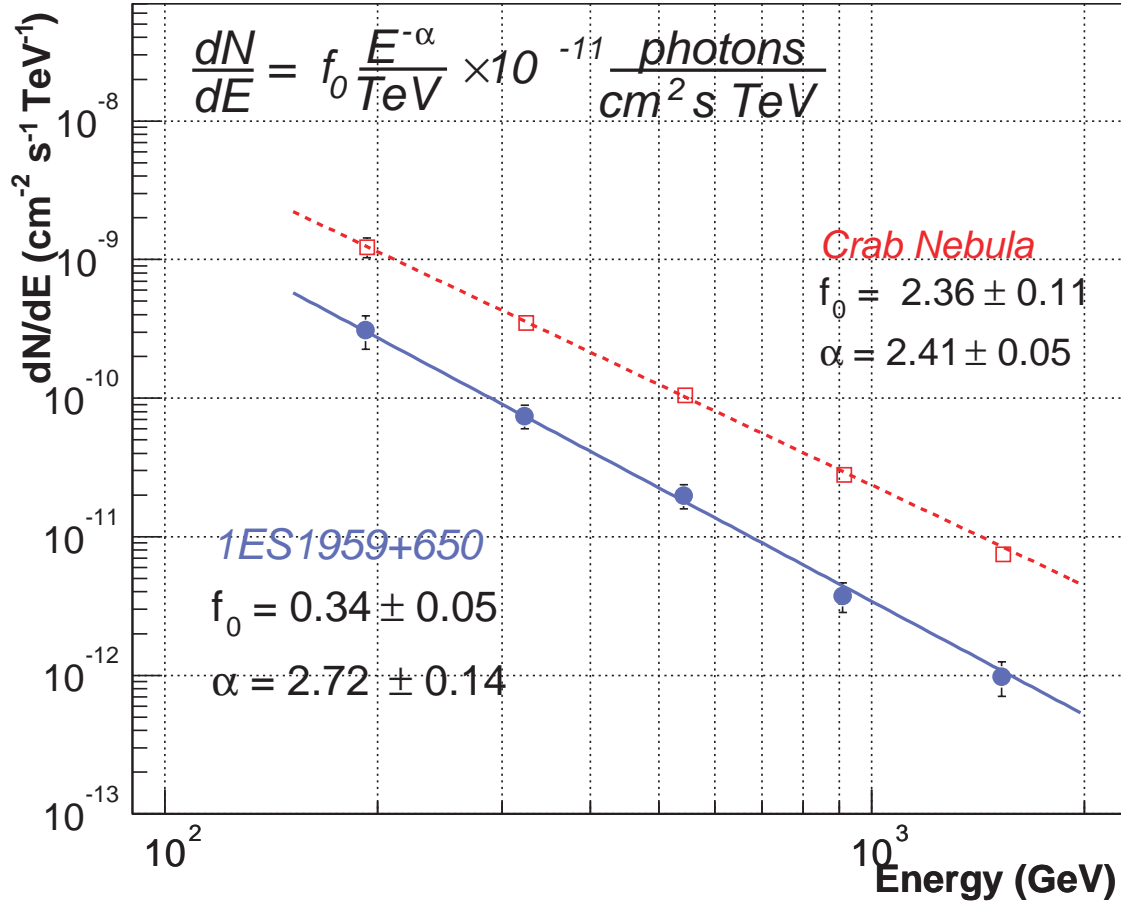


Fig. 5.— *Differential spectra for Crab and 1ES1959+650. The energy range from 150 GeV to 2 TeV is divided into five bins in logarithmic scale. The point positions are the median values of the estimated energy bins, weighted with the assumed spectral slope.*

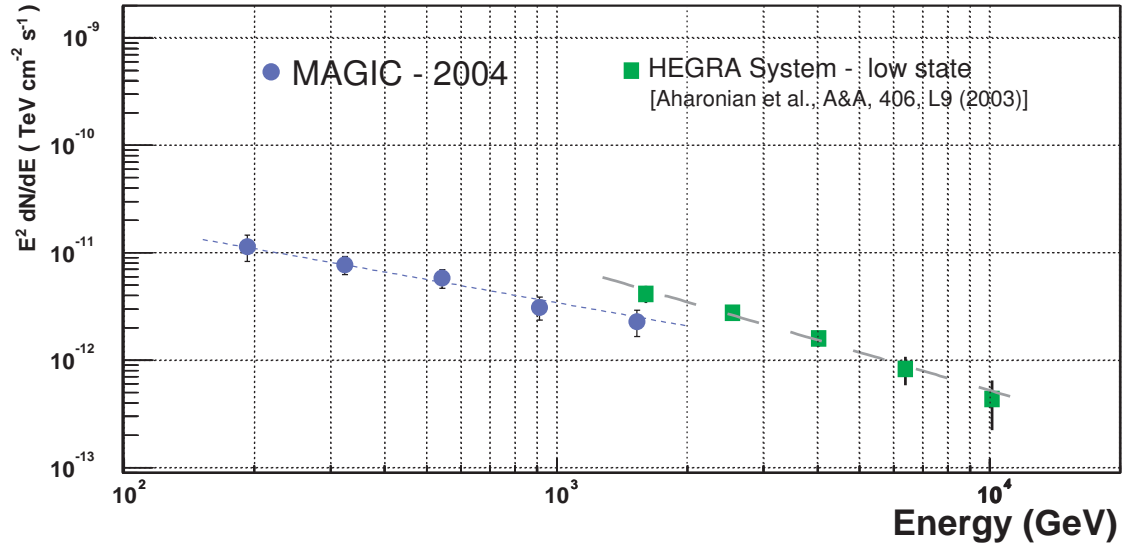


Fig. 6.— *Differential spectrum for 1ES1959+650, combined with HEGRA points from (Aharonian et al. 2003). Note that the HEGRA points are also from a low state of activity, but that there is no unique definition of 'low state'.*